

Temperature Fluctuation Characteristics of Liquid Lead-Bismuth in Complex Flow Structures

Authors: Meng Shuqi, Li Fengchen, Bin Qiu, Lin Jiming, Cai Dechang, Han Bin, Li Li, Hu Yisong

Date: 2025-07-07T00:00:00+00:00

Abstract

Lead-Bismuth Eutectic (LBE) alloy has become one of the main candidate materials for primary loop coolant in Generation IV reactors due to its high thermal conductivity, high heat capacity, and capability to operate at high temperatures under atmospheric pressure. Insufficient mixing of non-isothermal liquid LBE in the complex structures of the upper plenum can cause aperiodic temperature fluctuations, which affect the integrity of reactor structural materials, representing a thermal-hydraulic phenomenon that requires focused attention in reactors using LBE as the primary loop medium. Based on publicly available experimental data from liquid sodium parallel triple-jet tests, this paper comparatively analyzes the applicability of different turbulence models in simulating temperature fluctuations, and further compares the temperature fluctuation intensity between LBE and liquid sodium in parallel triple-jet configurations. On this basis, employing the validated Large-Eddy Simulation (LES) method, a study on the characteristics of temperature fluctuations of LBE in the complex flow structures of a reactor upper plenum was conducted. The results show that: the temperature fluctuation intensity of LBE is mainly concentrated in the 1~10 Hz range, belonging to typical low-frequency fluctuations; the region with the most intense temperature fluctuations is located at approximately 3/4 of the height between the core outlet and the hot leg; while at the far end of the core outlet, due to more sufficient mixing of non-isothermal LBE, its temperature fluctuation intensity is significantly reduced. The research findings can provide important references for thermal fatigue assessment of structural materials and reactor measurement point arrangement.

Full Text

Temperature Fluctuation Characteristics of Liquid Lead-Bismuth in Complex Flow Structures

MENG Shuqi^{1,2}, LI Fengchen³, QIU Bin², LIN Jiming², CAI Dechang², HAN Bin⁴, LI Li¹, HU Yisong²

¹Harbin Engineering University, College of Materials Science and Chemical Engineering, Harbin 150001, China

²China Nuclear Power Technology Research Institute, Shenzhen 518000, China

³Tianjin University, Tianjin 300000, China

⁴Southeast University, Nanjing 210000, China

Abstract

Lead-Bismuth Eutectic (LBE) alloy has emerged as a primary candidate coolant for fourth-generation reactor primary circuits due to its high thermal conductivity, substantial heat capacity, and capability for high-temperature operation under atmospheric pressure. Inadequate mixing of non-isothermal liquid LBE within complex upper plenum structures can induce aperiodic temperature fluctuations that compromise the integrity of reactor structural materials, representing a critical thermal-hydraulic phenomenon for LBE-cooled reactors. Based on publicly available experimental data from liquid sodium parallel triple-jet tests, this study evaluates the applicability of various turbulence models for simulating temperature fluctuations and compares the temperature fluctuation intensities between LBE and liquid sodium in a parallel triple-jet configuration. Subsequently, the validated Large-Eddy Simulation (LES) method is employed to investigate temperature fluctuation characteristics of LBE in complex reactor upper plenum flow structures. The results demonstrate that LBE temperature fluctuation intensity is predominantly concentrated in the 1-10 Hz range, characteristic of low-frequency fluctuations. The most severe temperature fluctuations occur at approximately three-quarters of the height between the core outlet and the hot leg, while regions distal to the core outlet exhibit significantly attenuated fluctuation intensity due to more complete mixing of non-isothermal LBE. These findings provide crucial insights for thermal fatigue assessment of structural materials and optimization of measurement point placement in reactors.

Keywords: liquid lead-bismuth, temperature fluctuation, large eddy simulation, low-frequency fluctuation

Introduction

Lead-Bismuth Eutectic (LBE) alloy, with its low melting point, high boiling point, high thermal conductivity, high specific heat capacity, and ability to operate at elevated temperatures under atmospheric pressure, has become a leading candidate coolant for lead-cooled fast reactors [1]. In reactor systems,

when coolant exits different fuel assemblies at varying temperatures, insufficient mixing between hot and cold fluids generates temperature oscillations in mixing regions, creating temperature variations with specific amplitudes and frequencies [2]. These fluctuations propagate to adjacent solid surfaces through thermal conduction and convection, causing surface temperature pulsations that induce thermal stress and fatigue issues. Simultaneously, this phenomenon compromises accurate measurement of core outlet temperatures, posing challenges to reactor safety [3].

Previous research on fluid temperature fluctuations includes several key contributions. Regarding thermal mixing mechanisms: Evrim [4] investigated thermal mixing processes of water in T-junctions of various sizes using data from Stuttgart University's fluid-structure interaction facility; Kamide et al. [5] experimentally studied cold-hot water mixing in tees using thermocouples and visualization techniques, identifying the momentum ratio of cold and hot fluids as the critical factor affecting water temperature fluctuation intensity; Aizawa et al. [6] demonstrated through high-temperature, high-pressure water mixing experiments that gravitational effects significantly influence thermal mixing; additional studies by Kuschewski, Miyoshi, Walke, and Li Zewei [7-10] further examined thermal mixing characteristics in T-junction configurations. Concerning temperature fluctuation mechanisms and response characteristics: Kimura [11] conducted liquid sodium jet experiments in a parallel triple-jet configuration, revealing that near-wall temperature fluctuations were significantly weaker than those in the bulk flow and that flow velocity had minimal impact on sodium temperature fluctuations; Wakamatsu [12] investigated the influence of upstream elbows in main pipes through water experiments in tees and bends, showing that time-averaged temperatures of fluid and solid surfaces nearly coincided with the mean temperature curve of cold-hot jets, while solid surface temperature fluctuations were substantially smaller than fluid fluctuations.

In numerical simulation: Cao et al. [13] employed Large Eddy Simulation (LES) to analyze temperature fluctuation patterns and distributions of liquid sodium in a simplified model, referencing flow velocity and temperature parameters from China's Experimental Fast Reactor; Lyu [14] established an equivalent model of the core outlet region based on the same reactor's thermal parameters and performed Computational Fluid Dynamics (CFD) analysis, finding that temperature difference between cold and hot fluids minimally affected sodium temperature fluctuation frequency but significantly impacted amplitude; Wang et al. [15] simulated temperature fluctuations at the core outlet of a lead-cooled fast reactor using LES in a simplified model, characterizing axial distribution features and establishing dimensionless analysis methods for amplitude, Power Spectral Density (PSD), and root-mean-square temperature; Cheng et al. [16] compared various eddy viscosity and Reynolds stress models for high-Reynolds-number liquid metal flow and heat transfer, concluding that the realizable k-model had lower precision requirements for wall functions; Shams and Zhao et al. [17-20] also conducted optimization work on Reynolds heat flux-related CFD models for liquid metal turbulent heat transfer.

Overall, existing research primarily focuses on temperature fluctuation characteristics of water and liquid sodium, with limited studies on LBE temperature fluctuation mechanisms and behavior in complex reactor flow structures. This paper first analyzes the applicability of different turbulence models for simulating temperature fluctuations based on publicly available liquid sodium parallel triple-jet experimental data, then compares temperature fluctuation intensity differences between LBE and liquid sodium in this configuration, and finally employs the validated LES model to investigate LBE temperature fluctuation characteristics in a reactor upper plenum. The obtained data provide references for thermal fatigue analysis and upper plenum measurement point optimization in LBE-cooled reactors.

1.1 Numerical Simulation Methods

Fluid flow must satisfy three fundamental conservation laws: mass, momentum, and energy, collectively described by the Navier-Stokes (N-S) equations. Since the N-S equations require additional closure relations, turbulence models are introduced [21]. Currently, widely used numerical methods include Direct Numerical Simulation (DNS), Reynolds-Averaged Navier-Stokes (RANS), and Large-Eddy Simulation (LES). DNS demands extremely high computational resources and remains impractical for engineering applications.

The governing equations are:

$$\frac{\partial u_i}{\partial x_i} = 0$$
$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j^2} + f_i$$
$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u_j \frac{\partial T}{\partial x_j} = \lambda \frac{\partial^2 T}{\partial x_j^2} + S$$

where u_i represents velocity ($\text{m} \cdot \text{s}^{-1}$), p pressure (Pa), ρ density ($\text{kg} \cdot \text{m}^{-3}$), f_i body force ($\text{m}^2 \cdot \text{s}^{-1}$), T temperature (K), S heat source term ($\text{W} \cdot \text{m}^{-3}$), and c_p specific heat capacity ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$).

RANS employs statistical averaging to partially solve the N-S equations, constructing turbulence models to close all Reynolds stress terms without computing turbulent fluctuations. This approach requires fewer grid cells and permits larger time steps, enabling engineering feasibility. RANS models can be further categorized into realizable k- ϵ , SST k- ω , and Detached Eddy Simulation (DES) based on different boundary layer treatments. However, since RANS neglects turbulent fluctuations, its capability for simulating transient pulsation processes may be insufficient. Consequently, the LES model was developed to balance computational resources and solution accuracy. In LES, large-scale eddies are

directly resolved while small-scale eddies, which generally exhibit isotropic characteristics, are simplified using time-averaged methods [22]. To address poor resolution of near-wall shear flows, Wall-Modeled LES (WMLES) was developed as an optimized alternative to classical LES. This hybrid approach combines RANS and LES advantages, using RANS in near-wall regions and switching to LES in outer regions. WMLES enables computations of bounded flows at high Reynolds numbers while relaxing stringent grid resolution requirements near walls. The governing equations are:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_{t,h}) \frac{\partial \bar{u}_i}{\partial x_j} \right]$$

where t is time (s), u velocity component ($\text{m} \cdot \text{s}^{-1}$), x spatial coordinate, μ dynamic viscosity ($\text{Pa} \cdot \text{s}$), Pr Prandtl number, and $Re = \frac{\rho u L}{\mu}$ the dimensionless ratio of inertial to viscous forces.

The ability of these methods to simulate LBE temperature fluctuations requires validation against experimental data. Currently, few LBE temperature fluctuation experiments are available; therefore, this study validates CFD models using publicly available liquid sodium temperature fluctuation experimental data before applying the validated models to LBE simulations.

1.2 Mechanism Experiments

Temperature fluctuation phenomena of liquid metal in reactor upper plenums arise from non-uniform flow velocities and temperatures at core outlet fuel assemblies. In pool-type spaces, these fluids undergo unsteady thermal mixing, creating complex thermal-hydraulic phenomena. Due to experimental facility limitations, direct temperature fluctuation tests on complex liquid metal reactor upper plenum structures are challenging. Researchers typically abstract this phenomenon as non-isothermal, non-isokinetic parallel jet thermal mixing and conduct studies based on parallel multi-channel configurations. Parallel triple-jet sodium temperature fluctuation experimental data published by Japan in the 1990s have been incorporated into international CFD benchmark databases [3]. This dataset enables quantitative comparison of different turbulence models' applicability for simulating temperature fluctuations.

[Figure 1: see original paper] shows a schematic of the liquid sodium temperature fluctuation experimental facility [3,23]. The channel height is 85 mm with rectangular jet nozzles measuring 20 mm \times 180 mm. Perforated plates and quadrant reducer nozzles upstream of the jets ensure uniform coolant velocity at the inlet cross-section. The nozzles and mixing region are sandwiched between two vertical stainless steel test plates, with fluid temperatures measured by a movable, non-contact K-type thermocouple array. Thermocouple accuracy is $\pm 0.1^\circ\text{C}$ with a 20 ms time constant. Temperatures in both solid and fluid are measured simultaneously at each thermocouple array position for a total du-

ration of 200 s. Due to significant differences in specific heat capacity between fluid and solid, different measurement frequencies are used: 0.01 s per measurement for fluid temperature and 0.1 s per measurement for solid temperature.

1.3 Temperature Fluctuation Intensity Characterization

The dimensionless temperature is defined as:

$$\theta = \frac{T_i - T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}}$$

where T_i is instantaneous temperature (K), T_{cold} cold fluid inlet temperature (K), and T_{hot} hot fluid inlet temperature (K).

The dimensionless time-averaged temperature is:

$$\bar{\theta} = \frac{1}{N} \sum_{i=1}^N \theta_i$$

where N is the total number of instantaneous temperature data points.

Power Spectral Density (PSD) is commonly employed for temperature fluctuation frequency analysis. This method applies Fast Fourier Transform to temperature fluctuation amplitude curves, converting time-domain temperature data to frequency-domain representation. The discrete Fourier transform for signal $\phi(t)$ based on finite sampling points is expressed as:

$$\Phi(f_n) = \sum_{k=0}^{N-1} \phi(t_k) e^{-i2\pi nk/N}$$

where $n = 0, 1, 2, \dots, (N - 1)$.

PSD describes signal power distribution in the frequency domain, with units of amplitude squared:

$$\text{PSD}(f) = \frac{|\Phi(f)|^2}{f_0}$$

where f_0 is the fundamental frequency. Amplitude is the square root of PSD:

$$A(f) = \sqrt{2 \cdot \text{PSD}(f)}$$

where f is fluctuation frequency (Hz).

2.1 Computational Domain and Boundary Conditions

Based on the geometry of the liquid sodium temperature fluctuation experimental facility [3,21], a CFD model was constructed. As shown in [Figure 2: see original paper], liquid sodium flows from three parallel rectangular channels into a large rectangular mixing region. Each nozzle width is 5 mm with 50 mm spacing between them, and the fluid domain thickness is 180 mm.

Thermophysical property correlations for liquid sodium are [24]:

$$\rho_s = 1014 - 0.235 \cdot T_s$$

$$\lambda_s = 104 - 4.7 \times 10^{-2} \cdot T_s$$

$$c_{p,s} = 1658 - 0.8479 \cdot T_s + 4.454 \times 10^{-4} \cdot T_s^2$$

$$\eta_s = 4.94 \times 10^{-4} \cdot e^{754.1/T_s}$$

where ρ_s is density ($\text{kg} \cdot \text{m}^{-3}$), λ_s thermal conductivity ($\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$), $c_{p,s}$ specific heat at constant pressure ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), η_s dynamic viscosity ($\text{Pa} \cdot \text{s}$), and T_s temperature (K).

2.2 Validation Results

Polyhedral meshes were selected for their flexibility in handling complex geometries. Mesh sensitivity analysis boundary conditions were: liquid sodium medium, inlet velocity $0.5 \text{ m} \cdot \text{s}^{-1}$, side hot fluid temperature 763 K, center cold fluid temperature 676 K. [Figure 3: see original paper] presents cross-sectional average temperature results from 2-6 s for different turbulence models across various mesh cell counts. The SST k- ω , DES, and WMLES models require approximately 6 million, 11 million, and 15 million cells, respectively, to achieve mesh independence. These differences primarily stem from varying near-wall region assumptions in each turbulence model, which impose different mesh quality requirements.

CFD model settings determined through mesh independence analysis are summarized in , with total cell count of approximately 15 million ensuring mesh independence for SST k- ω , DES, and WMLES models. All three sodium jets have inlet velocity $0.51 \text{ m} \cdot \text{s}^{-1}$, with cold sodium at 577.65 K and hot sodium at 620.85 K. Wall boundaries are no-slip; pressure-velocity coupling uses the SIMPLEC (Semi-Implicit Method for Pressure-linked Equation Consistent) scheme; pressure and momentum discretization employ second-order schemes; energy discretization uses the QUICK (Quadratic Upstream Interpolation for Convective Kinematics) scheme. Turbulence models include SST k- ω , DES, and WMLES.

[Figure 4: see original paper] compares CFD-simulated and experimental sodium temperature fluctuations over 0-6 s. Normalized mean temperature results show minimal differences among SST $k-\omega$, DES, and WMLES models. However, when converting time-domain temperatures to frequency domain via PSD, the SST $k-\omega$ model loses considerable fluctuation information, while DES and LES models produce dominant frequencies closer to experimental values. Compared to DES, WMLES tolerates larger grid aspect ratios near walls, improving CFD model convergence. Additionally, existing temperature fluctuation CFD simulations predominantly use LES models, with no documented DES applications [13-14]. Therefore, WMLES is recommended for LBE temperature fluctuation simulations.

2.3 Comparison of Temperature Fluctuation Intensity Between LBE and Sodium

Using identical settings from , temperature fluctuation intensity differences between liquid LBE and sodium were compared in the parallel triple-jet configuration. LBE thermophysical property correlations are [24]:

$$\rho_L = 11096 - 1.3236 \cdot T_L$$

$$\lambda_L = 3.61 + 1.57 \times 10^{-2} \cdot T_L$$

$$c_{p,L} = 159 - 2.72 \times 10^{-2} \cdot T_L$$

$$\eta_L = 4.94 \times 10^{-4} \cdot e^{754.1/T_L}$$

where ρ_L is density ($\text{kg} \cdot \text{m}^{-3}$), λ_L thermal conductivity ($\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$), $c_{p,L}$ specific heat ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), η_L dynamic viscosity ($\text{Pa} \cdot \text{s}$), and T_L temperature (K).

[Figure 5: see original paper] compares temperature fluctuations of liquid LBE and sodium at measurement points A and B over 0-6 s. The dominant fluctuation frequency ranges from 1-10 Hz, characteristic of low-frequency pulsations. Under identical boundary conditions, LBE exhibits slightly higher temperature fluctuation intensity than sodium.

3.1 Computational Domain and Boundary Conditions

Based on reactor upper plenum design drawings from literature [25], the validated WMLES model was applied to investigate LBE temperature fluctuation characteristics in complex flow structures. The fluid domain is shown in [Figure 6: see original paper]. The reference reactor in [25] contains numerous fuel

assemblies; this study appropriately consolidated assembly numbers according to the overall upper plenum geometry.

CFD mesh settings follow with total cell count of approximately 50 million. Referencing core outlet thermal-hydraulic parameters from literature [26], constant inlet temperatures and mass flow rates were applied to each region as specified in .

3.2 Temperature Fluctuation Intensity at Typical Locations

[Figure 7: see original paper] illustrates the computational mesh and monitoring point arrangement, covering regions near the core outlet, pool-type large space, and hot leg attachment. Considering reactor power distribution and potential temperature measurement device locations, 54 monitoring points were established. The cross-section numbering on the right side of [Figure 7: see original paper] corresponds to the left-side cross-sections, indicating spatial positions at different heights.

To analyze temperature fluctuation characteristics after cold-hot LBE mixing, the temperature standard deviation at each monitoring point is defined by Eq. (23). Calculating the standard deviation of temperature data over time at each point reflects the degree of deviation from the mean value, thereby characterizing temperature fluctuation intensity:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (T_i - T_{\text{avg}})^2}$$

where N is the number of temperature measurements, T_i the instantaneous temperature at measurement i (K), and T_{avg} the mean temperature at that point (K).

[Figure 8: see original paper] shows the locations and temperature fluctuations of eight LBE monitoring points with intense pulsations ($\sigma \geq 20$ K) over 0–3 s. The results indicate that the most severe temperature fluctuations occur at approximately three-quarters of the height between the core outlet and hot leg, primarily due to intense thermal mixing effects as non-isothermal LBE jets enter the large plenum space. In regions distal to the core outlet, temperature fluctuation intensity significantly decreases due to more complete mixing of non-isothermal LBE. Furthermore, all monitoring points exhibit dominant frequencies below 10 Hz, characteristic of low-frequency fluctuations.

Conclusions

Based on parallel triple-jet experimental data, this study evaluated the applicability of different turbulence models for simulating liquid metal temperature fluctuations, compared temperature fluctuation differences between liquid LBE

and sodium, and numerically investigated LBE temperature fluctuation characteristics in complex flow structures. The main conclusions are:

- 1) LES models are more suitable than RANS models for simulating transient temperature fluctuation processes in liquid metals.
- 2) Under identical boundary conditions, liquid LBE exhibits slightly higher temperature fluctuation intensity than liquid sodium, with fluctuation frequencies in the 1-10 Hz range, characteristic of low-frequency pulsations.
- 3) In complex flow structures, the most intense LBE temperature fluctuations occur at approximately three-quarters of the height between the core outlet and hot leg, warranting focused attention in reactor thermal fatigue analysis and upper plenum measurement device placement.

Author Contributions

MENG Shuqi developed the numerical model, performed data analysis, and wrote the manuscript. LI Fengchen and QIU Bin conceived the research idea and critically reviewed and revised the intellectual content. LIN Jiming and CAI Dechang provided funding support. HAN Bin collected and processed public literature and data and supervised research progress. LI Li and HU Yisong provided guidance on the research methodology.

References

1. LI Kaixuan, ZHANG Zixiong, WEI Qianglin, et al. Impact and analysis of different coolants on the core physics parameters of lead-cooled fast reactors[J]. *Science Technology and Engineering*, 2024, 24(28): 12152-12158. DOI: 10.12404/j.issn.1671-1815.2310085.
2. Jones I S, Lewis M W J. A frequency response method for calculating stress intensity factors due to thermal striping loads[J]. *Fatigue & Fracture of Engineering Materials & Structures*, 1994, 17(6): 709-720. DOI: 10.1111/j.1460-2695.1994.tb00268.x.
3. Kimura N, Miyakoshi H, Kamide H. Experimental investigation on transfer characteristics of temperature fluctuation from liquid sodium to wall in parallel triple-jet[J]. *International Journal of Heat and Mass Transfer*, 2007, 50(9-10): 2024-2036. DOI: 10.1016/j.ijheatmasstransfer.2006.09.030.
4. Evrim C, Chu X, Laurien E. Analysis of thermal mixing characteristics in different T-junction configurations[J]. *International Journal of Heat and Mass Transfer*, 2020, 158: 120019. DOI: 10.1016/j.ijheatmasstransfer.2020.120019.
5. Kamide H, Igarashi M, Kawashima S, et al. Study on mixing behavior in a tee piping and numerical analyses for evaluation of thermal striping[J]. *Nuclear Engineering and Design*, 2009, 239(1): 58-67. DOI: 10.1016/j.nucengdes.2008.09.005.
6. Aizawa T, Masuda Y, Minami K, et al. Direct observation of

- channel-tee mixing of high-temperature and high-pressure water[J]. *The Journal of Supercritical Fluids*, 2007, 43(2): 222-227. DOI: 10.1016/j.supflu.2007.03.008.
7. Kuschewski M, Kulenovic R, Laurien E. Experimental setup for the investigation of fluid-structure interactions in a T-junction[J]. *Nuclear Engineering and Design*, 2013, 264: 223-230. DOI: 10.1016/j.nucengdes.2013.02.024.
 8. Miyoshi K, Kamaya M, Utanohara Y, et al. An investigation of thermal stress characteristics by wall temperature measurements at a mixing tee[J]. *Nuclear Engineering and Design*, 2016, 298: 109-120. DOI: 10.1016/j.nucengdes.2015.12.004.
 9. Walker C, Simiano M, Zboray R, et al. Investigations on mixing phenomena in single-phase flow in a T-junction geometry[J]. *Nuclear Engineering and Design*, 2009, 239(1): 116-126. DOI: 10.1016/j.nucengdes.2008.09.003.
 10. LI Zewei. Study on heat transfer characteristics of mixed flow in three-way pipe[D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2019. DOI: 10.27239/d.cnki.gnhhu.2019.001909.
 11. Kimura N, Ogawa H, Kamide H. Experimental study on fluid mixing phenomena in T-pipe junction with upstream elbow[J]. *Nuclear Engineering and Design*, 2010, 240(10): 3055-3066. DOI: 10.1016/j.nucengdes.2010.05.019.
 12. Wakamatsu M, Nei H, Hashiguchi K. Attenuation of temperature fluctuations in thermal striping[J]. *Journal of Nuclear Science and Technology*, 1995, 32(8): 752-762. DOI: 10.3327/jnst.32.752.
 13. Cao Q, Lu D G, Lyu J. Numerical investigation on temperature fluctuation of the parallel triple-jet[J]. *Nuclear Engineering and Design*, 2012, 249: 82-89. DOI: 10.1016/j.nucengdes.2011.07.018.
 14. Lyu Jing. Numerical simulation of coolant temperature fluctuation at the core outlet of China experimental fast reactor[D]. Beijing: North China Electric Power University, 2012.
 15. Wang L Z, Wu G W, Wang J, et al. Numerical investigation of the core outlet temperature fluctuation for the lead-based reactor[J]. *Annals of Nuclear Energy*, 2018, 117: 194-201. DOI: 10.1016/j.anucene.2018.03.020.
 16. Cheng X, Tak N I. CFD analysis of thermal-hydraulic behavior of heavy liquid metals in sub-channels[J]. *Nuclear Engineering and Design*, 2006, 236(18): 1874-1885. DOI: 10.1016/j.nucengdes.2006.02.001.
 17. Shams A, Roelofs F, Tiselj I, et al. A collaborative effort towards the accurate prediction of turbulent flow and heat transfer in low-Prandtl number fluids[J]. *Nuclear Engineering and Design*, 2020, 366: 110750. DOI: 10.1016/j.nucengdes.2020.110750.
 18. Shams A, De Santis A, Roelofs F. An overview of the AHFM-NRG formulations for the accurate prediction of turbulent flow and heat transfer in low-Prandtl number flows[J]. *Nuclear Engineering and Design*, 2019, 355: 110342. DOI: 10.1016/j.nucengdes.2019.110342.
 19. Sandberg R D, Zhao Y M. Machine-learning for turbulence and heat-flux model development: a review of challenges associated with distinct physi-

- cal phenomena and progress to date[J]. International Journal of Heat and Fluid Flow, 2022, 95: 108983. DOI: 10.1016/j.ijheatfluidflow.2022.108983.
20. Zhao Y M, Akolekar H D, Weatheritt J, et al. RANS turbulence model development using CFD-driven machine learning[J]. Journal of Computational Physics, 2020, 411: 109413. DOI: 10.1016/j.jcp.2020.109413.
 21. TAO Wenquan. Numerical heat transfer[M]. 2nd ed. Xi'an: Xi'an Jiaotong University Press, 2001.
 22. ZHANG Zhaoshun, CUI Guixiang, XU Chunxiao. Theory and application of numerical simulation of turbulent large eddy[M]. Beijing: Tsinghua University Press, 2008.
 23. Acton M, Lenci G, Baglietto E. Structure-based resolution of turbulence for sodium fast reactor thermal striping applications[C]. NURETH-16, Chicago, USA. August 30–September 4, 2015.
 24. OCDE, AEN. Handbook on lead-bismuth eutectic alloy and lead properties, materials compatibility, thermal hydraulics and technologies[M]. Paris: OCDE Publishing, 2015.
 25. Yoshikawa S, Minami M. Data description for coordinated research project on benchmark analyses of sodium natural convection in the upper plenum of the MONJU reactor vessel under supervisory of technical working group on fast reactors[R]. International Atomic Energy Agency, Vienna, 2008.
 26. ZHU Huanjun, XU Yijun. Numerical analysis of temperature fluctuation in core outlet region of China experimental fast reactor[J]. Atomic Energy Science and Technology, 2014, 48(1): 54–60. DOI: 10.7538/yzk.2014.48.01.0054.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.